

ACTIVE REGIONS

1: *The Occurrence of Solar Flares and the Development of Active Regions*

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Abstract. A summary of data on the occurrence of flares and the development of active regions, based on cinematographic data is given. It is shown that flare frequency is determined by the orientation of the magnetic axis relative to the direction of solar rotation and the morphology of the magnetic field as seen in $H\alpha$. In particular, flares are most numerous in simple round spots with reversed polarity nearby, although they may also be frequent in complex spots with polarity reversal.

Important solar active regions are shown to evolve principally along two lines; typically they appear as bright regions with loops and grow rapidly to stable bipolar magnetic form. Important activity will occur as the result of later growth of following polarity ahead of the main spots, or some other source of reversal. However, some groups appear as reversed polarity regions and grow rapidly to a level of extreme activity.

A series of papers giving case histories is promised.

1. Introduction

In 1967, the author and colleagues began operation of small photoheliographs in Pasadena and Tel Aviv in 1968, with the object of obtaining high-resolution films of solar flares. A larger telescope was later devoted to the same purpose; first, in Pasadena and, subsequently, at the Big Bear Solar Observatory. All three instruments could only photograph part of the Sun; consequently, we had to choose those active regions most likely to produce interesting flares. After not many months, we found our selectivity was not very good at all. We usually followed either the most complex region on the Sun or the brightest plage seen in $H\alpha$. Typically, while we were watching some huge but inactive region with 100 spots and complex structure, big flares would occur in an undistinguished looking spot out of our field.

Since that time, we have accumulated many miles of film, the study of which has given us better understanding of the places where flares occur. Of course, this matter has been studied by many authors, and there are a number of conclusions, some contradictory (otherwise, we would not have had so much difficulty choosing which region to follow). The high spatial resolution and continuity of our $H\alpha$ records allow us to study the development of active regions and the occurrence of flares in greater detail, and we feel that we can improve on the previous conclusions.

We shall present in this series case histories of several active regions or interesting flares. Many are different, but certain important regularities appear. Solar activity is very complex, and one does best to study each region in detail. But to save the reader the suspense, we present our preliminary conclusions in this introductory paper.

2. The Occurrence of Solar Flares

Considerable attention has been devoted to the connection between the magnetic classification of sunspots and associated flare activity. It has been generally supposed that flares are most frequent in groups classified $\beta\gamma$ and δ . However, we found to our dismay in the last year that often the flares occurred in regions classified αp , although these regions might eventually reach $\beta\gamma$ or δ status. Examination of the material showed that it is not the umbral fields alone that matter, but the distribution of strong fields of less than spot strength, which may be evaluated through the appearance of the group in $H\alpha$. This result is logical, because, after all, the flares do not occur over the sunspots, but in the neighboring plage. Therefore, *we must examine that plage* to determine the activity to be expected.

We have found the following factors to be connected with a high-frequency of solar flares:

(1) Reversed polarity, either (and usually) following plage and satellite spots developing ahead of a large preceding spot, or a preceding spot developing behind a region of \mathcal{F} polarity (Henceforth, we designate all polarity \mathcal{P} or \mathcal{F} , depending on whether it should be preceding or following in the hemisphere.)

(2) Steep field gradients, as evidenced by the encroachment of bright plage on a large umbra. This is particularly important if the polarity is inverted.

(3) The emergence of new sunspots, particularly in existing regions or old sunspots breaking up.

(4) In regions where other flares have occurred. (This covers many cases where we do not understand the reason for the flares.)

(5) Filaments imbedded in bright plage.

Large flares are unlikely to occur in stable bi-polar regions, particularly those dominated by a large preceding spot surrounded by anti-plage.

All these possibilities have been mentioned at one time or another. Smith and Howard (1968) define a class of 'reversed polarity' and state that these and regions of complex magnetic polarity are three times as flare productive as simple regions. We find that complex regions produce small flares, but do not produce many large flares; most large flares are connected with reversed polarity, even though these regions are relatively rare.

Smith and Howard did not explicitly define reversed polarity, although we may presume that they meant exactly that. We wish to define inverted polarity more specifically. Draw a line between the center of \mathcal{F} polarity and the center of \mathcal{P} polarity. If that line is rotated 60° or more to the normal sense, the polarity is inverted. This rule applies to each individual region of polarity; a normal bi-polar region may show a small area of \mathcal{F} polarity preceding the preceding spot; that area is termed 'inverted' even though a large \mathcal{F} region follows the main spot. Bumba *et al.* (1968) state without reservation that all active regions with more than 10 flares develop where "newly developed magnetic field of the \mathcal{F} polarity is strongly compressed between the large-scale patterns of the magnetic field of the leading polarity". They are correct, with

the addition of the inverse case of the emergence of \mathcal{P} polarity behind \mathcal{F} . Thus, the key element is field reversal. Figure 1 shows Mt. Wilson 17229, a spot classified αp or J, which had a 90° polarity rotation, and bright plage close to the umbra. Although the standard attitude is that such spots are old and inactive, it produced a number of large flares, and may be regarded as the prototype of extremely active, inverted polarity spots. Figures 2a, b show the inverse case of \mathcal{P} polarity following \mathcal{F} .

Severny pointed out long ago the occurrence of flares along neutral lines; but since all spot groups have neutral lines, this condition is necessary but not sufficient. It is true that once a flare has begun, brightness will spread along the neutral line, probably because the field is horizontal there. But, we find the beginning point of flares does not have to be on a neutral line – more often, it is in the \mathcal{F} polarity region.

Rust (1968) was first to draw attention to the importance of small satellite spots; his Figure 2 shows the occurrence of many surges at a point of weak inverted polarity.

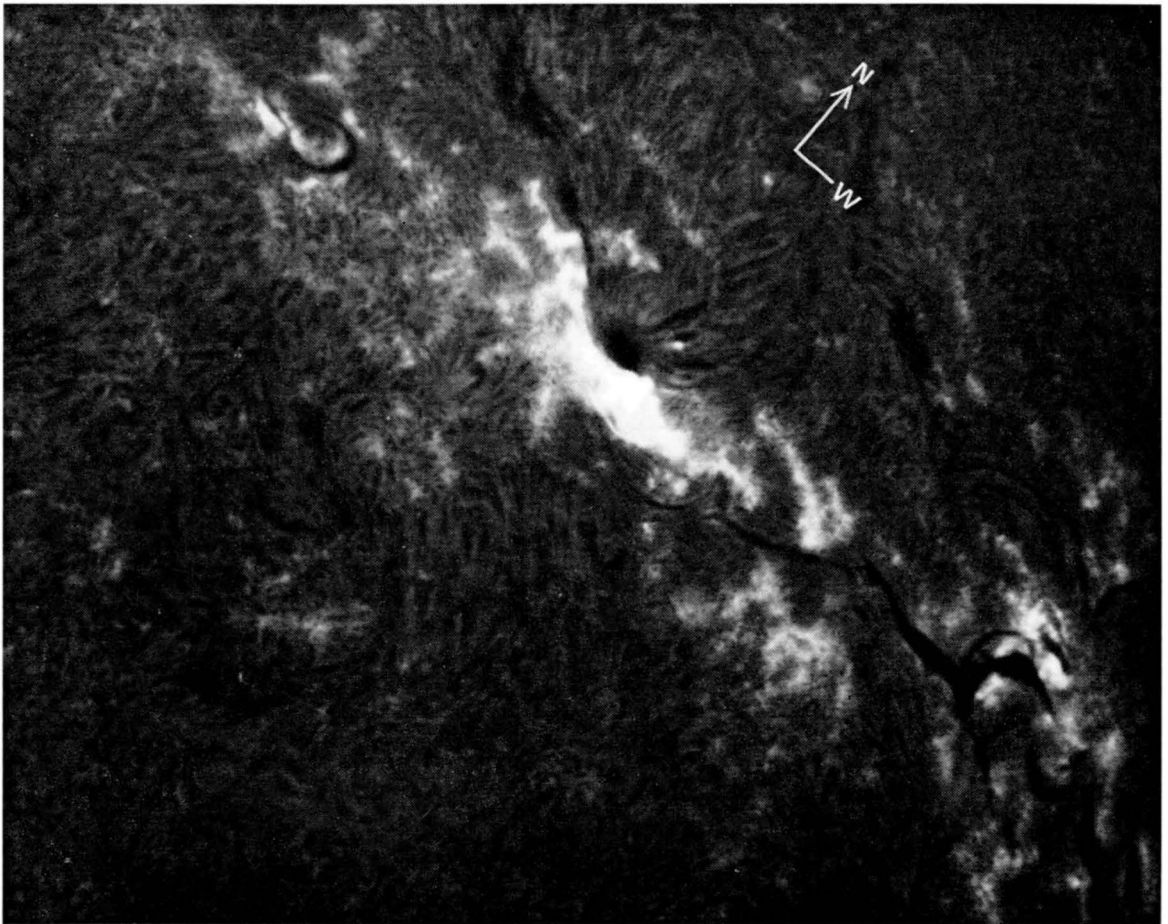


Fig. 1. Mt. Wilson 17229, photographed April 20, 1969 (All photos made with the Caltech 5-inch Photoheliograph, unless otherwise noted. Observer, Roger Chevalier. All figures are oriented with geocentric North top, West right.) This round αp spot was bordered on the south by bright following plage through its disk passage. Numerous bright flares occurred along the line of this plage. On the 20th, new field began to erupt south preceding marked by extremely bright plage. Although such field must erupt symmetrically the \mathcal{P} polarity either disappears or merges with the main spot, and only \mathcal{F} polarity remains in the erupting region. A series of large flares occurred in the days succeeding the development of the new inverted polarity.

More important, it shows the occurrence of a number of flares at a region of inverted polarity in the following part of the region, where a group of small preceding spots are following a region of following polarity. We have found the role of satellite spots quite important in small surges. Typically, one finds a small bright $H\alpha$ plage (indicating the presence of \mathcal{F} polarity) appearing in the penumbra of a large preceding spot, and numerous horizontal surges, seldom of great importance, will then occur, always flowing radially from the main spot toward the region of opposite polarity. This obeys the general rule that *flare excitation usually flows away from the large sunspot*.

Although these ideas have been developed from the study of recent spot groups, reference to older work shows the importance of inverted polarity. Figure 2 of our paper on the September 1963 group (Zirin and Werner, 1967) shows the extensive region of \mathcal{F} polarity leading the large preceding spot. Figure 1 of our paper on the August 28, 1966 flare (Zirin and Lackner, 1968) shows the N-S division of polarity, with bright plage leading the spot (suggesting inverted polarity). The flare began ahead of the main spot.

The connection of flare occurrence with the appearance of new spots has been suggested by previous work. Martres *et al.* (1968a) have discussed the connection of flares with 'structure magnétique évolutive', (SME) which they elsewhere (Martres *et al.*, 1968b) termed EF – evolutionary feature. In our data the SME are mostly important when they are connected with polarity inversion. Emerging flux inside spot groups usually produces only small flares, but when it appears ahead of spot groups, large events may follow. In the second paper of this series, we will describe the large flares connected with the disappearance of an old spot and birth of a new one on September 25–26, 1968; we have other records of numerous small flares connected with the appearance of new spots in the middle of a large active region. These spots are usually round and dark. On October 25, 1969 (see Figure 7 and caption), we observed a 1B flare in connection with the emergence of a satellite spot of \mathcal{F} polarity next to the dominant preceding spots of the group; this was followed by some activity for a few days, but soon died out; there is no fixed rule for the development of inverted polarities.

Imbedded filaments are not numerous, but they form a well-defined class of flare. An example is that of September 11, 1968 (Vorpahl and Zirin, 1970). Normally, filaments appear in dark regions of horizontal field separating bright regions of opposite vertical magnetic fields. If the filament is directly above a bright region, the field must be vertical at the surface and horizontal at the filament height; this situation seems unstable.

3. The Development of Active Regions

Because the conditions for flare occurrence depend so clearly on the magnetic peculiarities of the active region, they must be connected with the development of the region. Our data give us an excellent opportunity to study the development of active regions, and correlation of the observed $H\alpha$ structure with the magnetic field by use

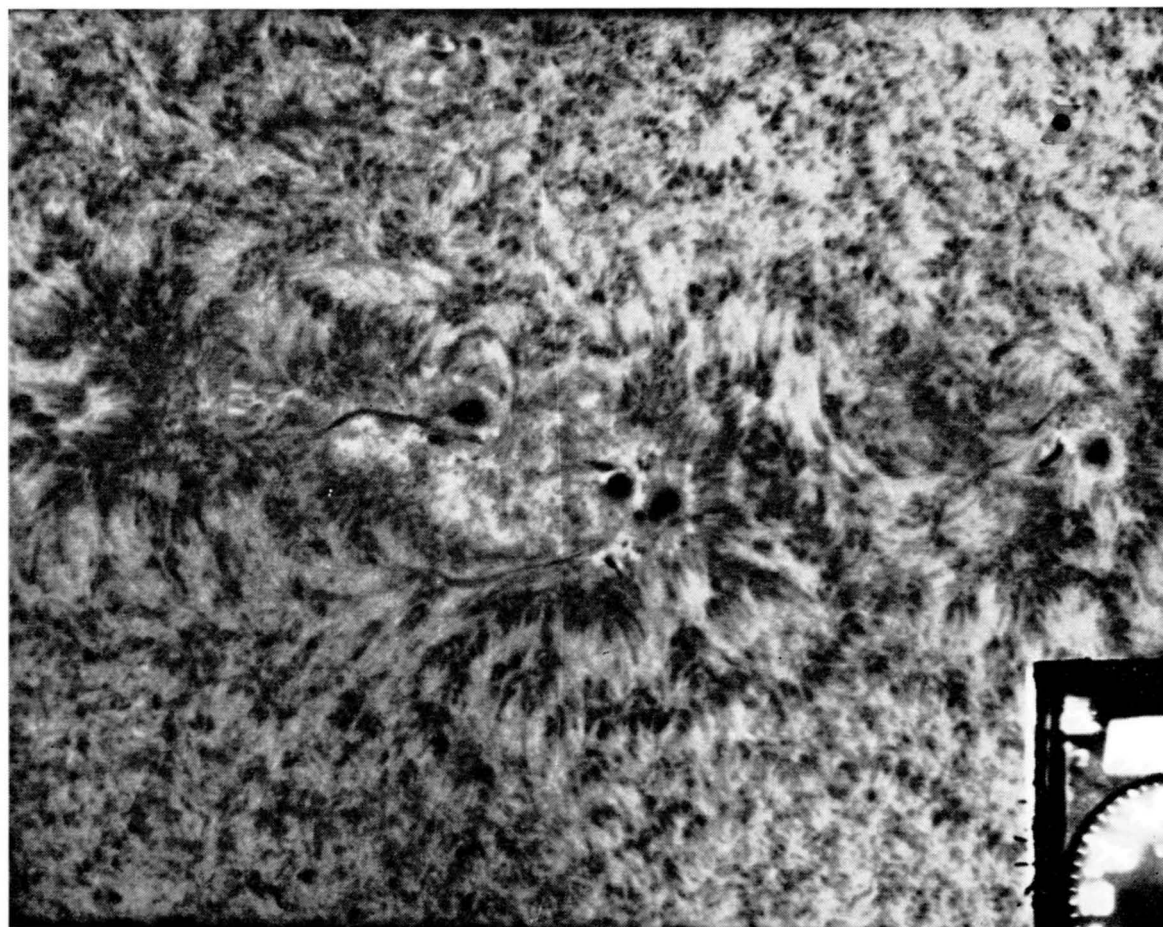


Fig. 2a. Mt. Wilson 16877–8, July 13, 1968. (Observer, Chevalier.) A large spot of \mathcal{P} polarity is following the group. From right the large spots have polarities \mathcal{P} , \mathcal{F} , \mathcal{P} . The disturbed region in between is \mathcal{F} . Polarity boundary is marked by a filament curling round the spot.

of the chromospheric magnetograph (Veeder and Zirin, 1970) allows us to evaluate the field changes. Unfortunately, our material only covers 1968 and 1969, so it may be influenced by the type of spots current in this period; but comparison with more limited data from earlier years shows the results to be typical.

The key feature in recognizing development of active regions is the bright region with loops (BRL) (Weart and Zirin, 1969) termed active filament systems (AFS)* by Bruzek (1968) who was the first to recognize their significance in active regions, but did not realize that they marked the birth of new groups as well. Weart and Zirin show that every case of the emergence of a new sunspot group was marked by a BRL, and that the direction of the filaments showed the direction of the lines of force connecting the emerging fields.

* We prefer to retain our terminology because the BRL are quite unrelated to filaments; for that matter, they are also unrelated to loop prominences, for they have been shown by Roberts (1969) to be very low-lying arches only a few thousand km high. Hopefully, further study will produce a more accurate name that all might agree on – possibly ‘emerging field regions’ might be useful.

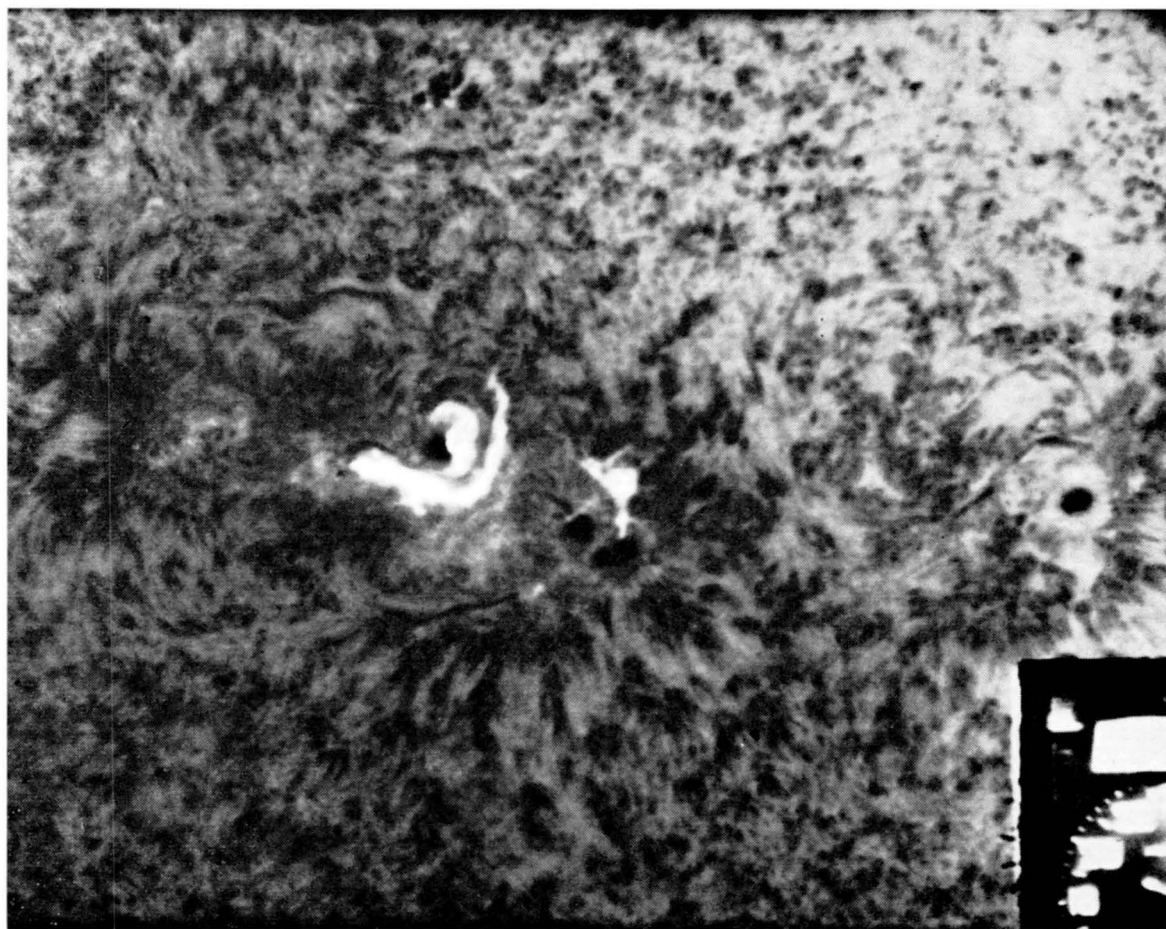


Fig. 2b. 2B flare, 0011/19 UT July 12 (observer, Zirin) occurring along the neutral line. This flare began with rising of the filament and violent motion along the neutral line. The Class 3 flare July 9 was homologous. This region formed on the backside and was rather young for such complex structure.

We have seen two distinct patterns of development of the most active regions. The first is most common:

(1) A BRL appears and grows in 5 or 6 days into a bi-polar spot group, the preceding and following spot rapidly separating in longitude. The group stabilizes for a while, usually with decay of the following spot. Then, one or two rotations after the birth of the group, a bright plage, often of the BRL form, appears on the leading edge of the preceding spot and grows rapidly, accompanied by many flares. This plage almost always is predominantly following polarity (presumably the \mathcal{P} polarity merges with the main spot) and inverted polarity results.

(2) A BRL emerges with complex or inverted orientation, grows rapidly in the course of a day, produces several moderate to large flares, and stabilizes to an inactive bi-polar group.

(3) A BRL emerges with inverted polarity, grows continuously in 4 or 5 days to great size, producing very large flares at maturity.

(4) Two spot groups merge so that a preceding spot is directly adjacent to the following plage of the first.

The prototype of Class 1 is Mt. Wilson 16951 (McMath 9634) which was born (Figures 3a–d) September 1, 1968 at one end of an older east–west filament (many spot groups are born in pre-existing filaments, but we have no statistical study as yet). It grew rapidly to large bi-polar size without great activity but with numerous small flares. It returned as Mt. Wilson 17000 (McMath 9692) with moderate activity and a single preceding spot. For this reason, we have few photos of it at Caltech, but the ESSA daily photos show development of moderately bright plage ahead of the spot as it passed off the limb. When it returned on October 22 as Mt. Wilson 17033 (McMath 9740), it showed a huge preceding spot completely surrounded by \mathcal{F} polarity, and a series of great flares centered on small satellite following spots, both following and preceding it. (Figure 4.)

Another good example is Mt. Wilson 17097, which formed on the backside at the site of a filament steeply inclined (about 70°) to the north–south line. It was classified as βp on December 21, 1968, but bright \mathcal{F} polarity plage appeared ahead of the preceding spots (Figure 5) accompanied by small flares, and grew rapidly until it covered an extended region. A large flare (Figure 5b) occurred on the 29th. The group died out on the backside of the Sun.

The prototype of Class 2 is Mt. Wilson 16788 (McMath 9337) which was born 24 April, 1968 in the middle of an east–west filament. It had inverted polarity from the start and grew rapidly from 1500 to 2400 UT. A large flare at 0035 on the 25th climaxed this growth, and the next day the spot reappeared as a stable bi-polar group of normal polarity, which showed no further activity.

The prototype of Class 3 is Mt. Wilson 17097 (Figure 6) (McMath 8362) which appeared July 1, 1966 as a BRL of inverted (about 120° tilt) polarity which grew rapidly as two parallel strands of spots, without any change of tilt, until a huge flare occurred July 7, 1966.

The prototype of Class 4 is Mt. Wilson 17584 and 17586 (McMath 10432). In its first disk passage (Figure 7) October 1969 as Mt. Wilson 17535 (McMath 10385), it was a member of anti-class 1, viz. a large group dominated by a big preceding spot; thus, producing much less activity than might be expected, considering the number of spots, etc. All the activity occurred behind the big preceding spots. This group was following a smaller group, McMath 10381. When 10385 reappeared (Figure 8), it had lost its tail of following spots, and was climbing up the back of the former 10381 (all were now lumped as 10432), which had grown considerably in the meantime. There now was considerable activity in the region between the two big spots. The group reappeared in December more or less unchanged in structure, and decayed on the disk through gradual weakening of the magnetic fields.

These growth classes are not all-inclusive (indeed, our first detailed study, Mt. Wilson 16997, conforms only partially to Class 2), but they include the majority of very active groups. To them should be added anti-class 1: when a stable preceding spot surrounded by anti-plage forms, the group is finished so far as flares are concerned.

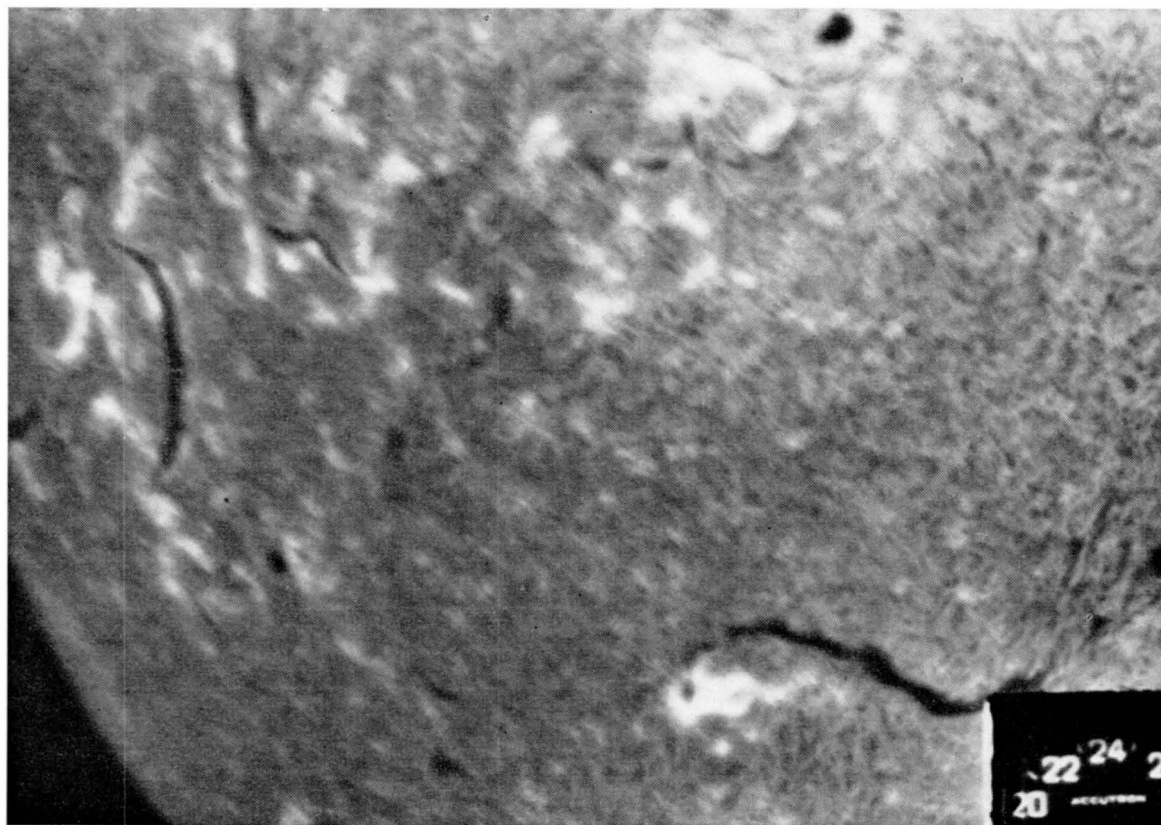


Fig. 3a. Birth of Mt. Wilson 16951 (lower right) as a bright loop region at the end of an isolated filament (September 1, 1968). Many new active regions erupt this way along filaments.

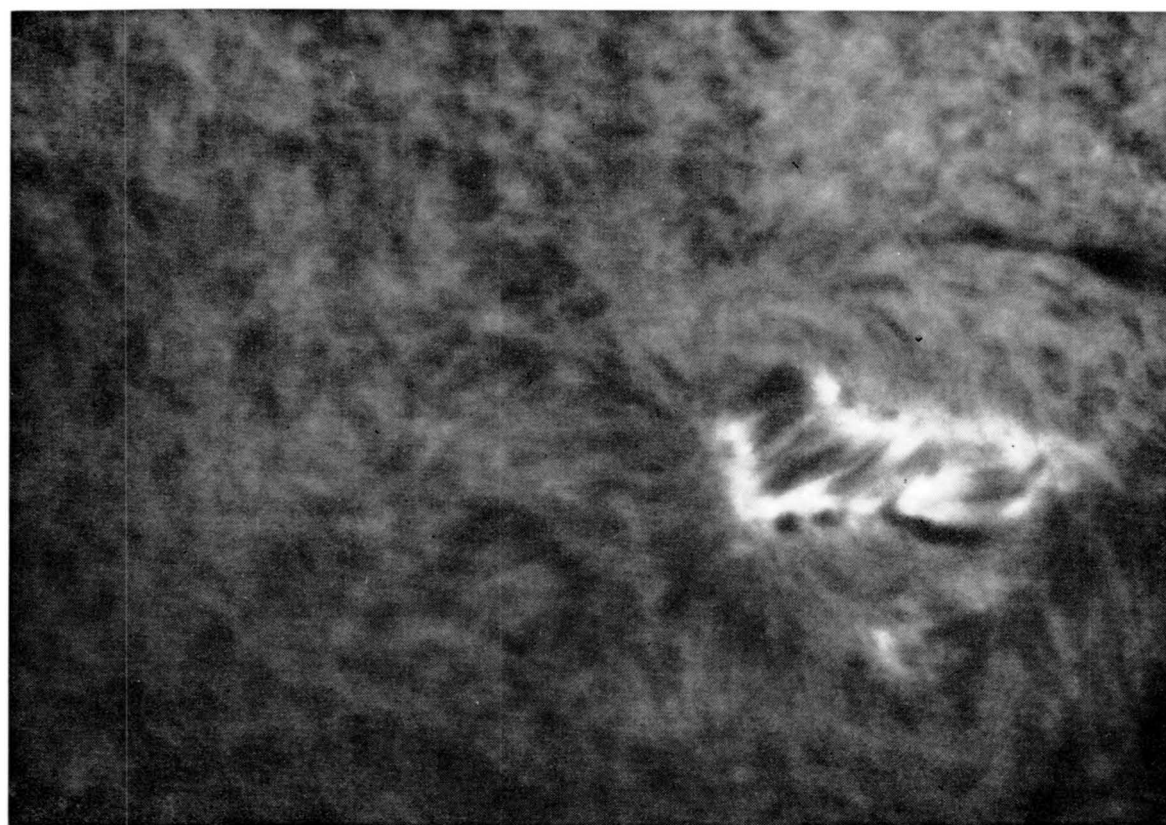


Fig. 3b. An enlarged off-band photo September 1, 1968, made with Ishak I.

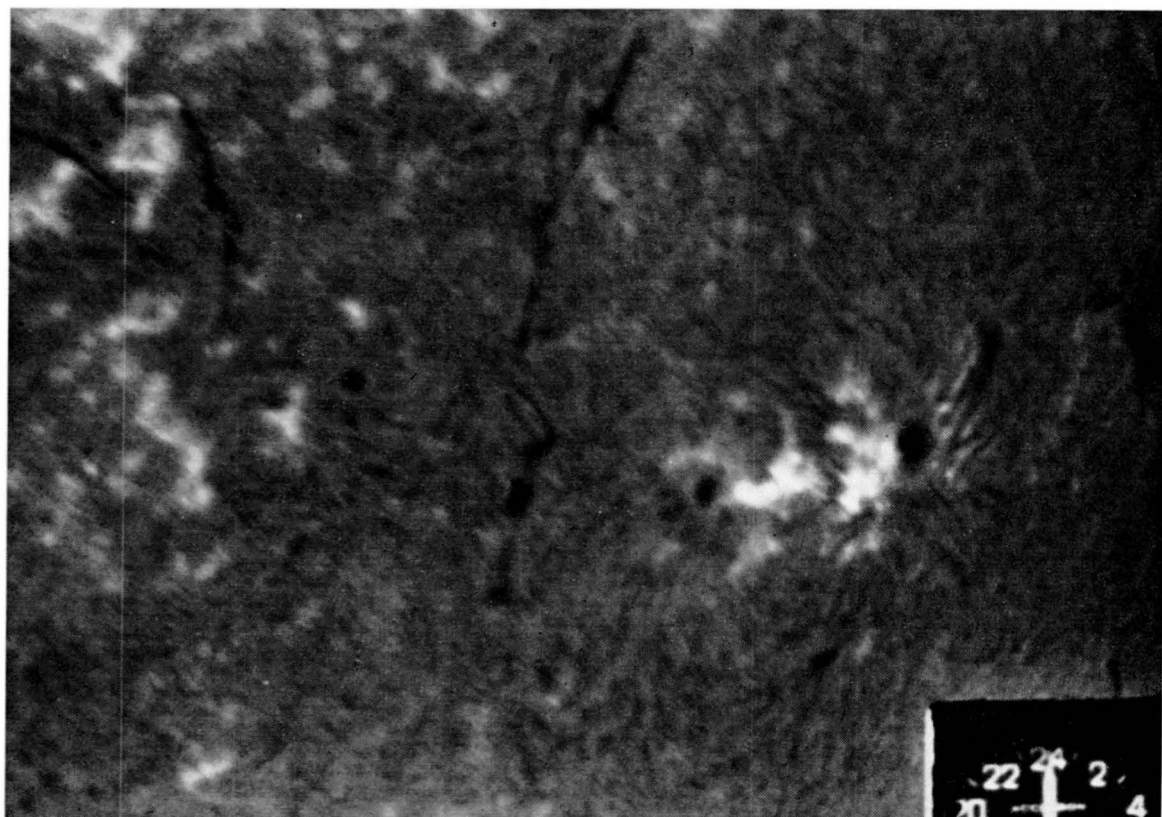


Fig. 3c. Further growth of Mt. Wilson 16951 September 6, 1968. It developed as a bi-polar group. These pictures are inferior because of a temporary optical misalignment.

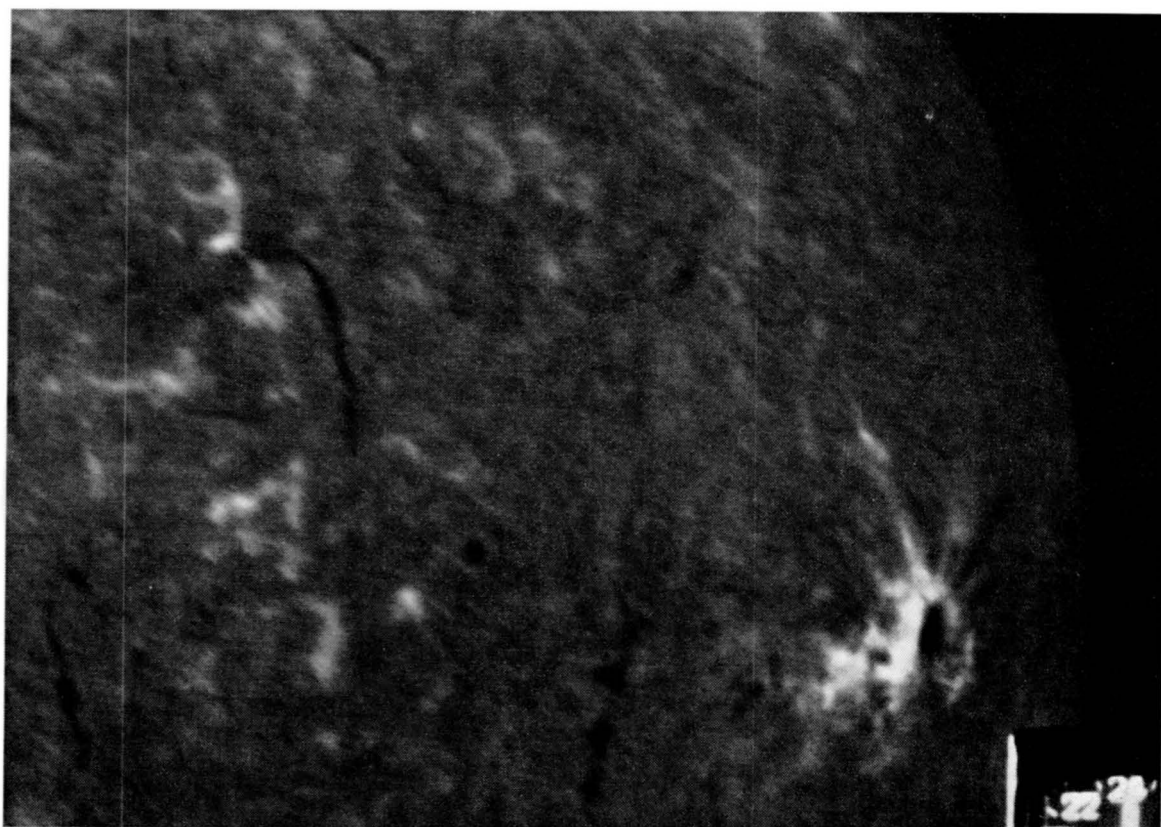


Fig. 3d. September 7, 1968. The following spot decayed as the region reached the limb.

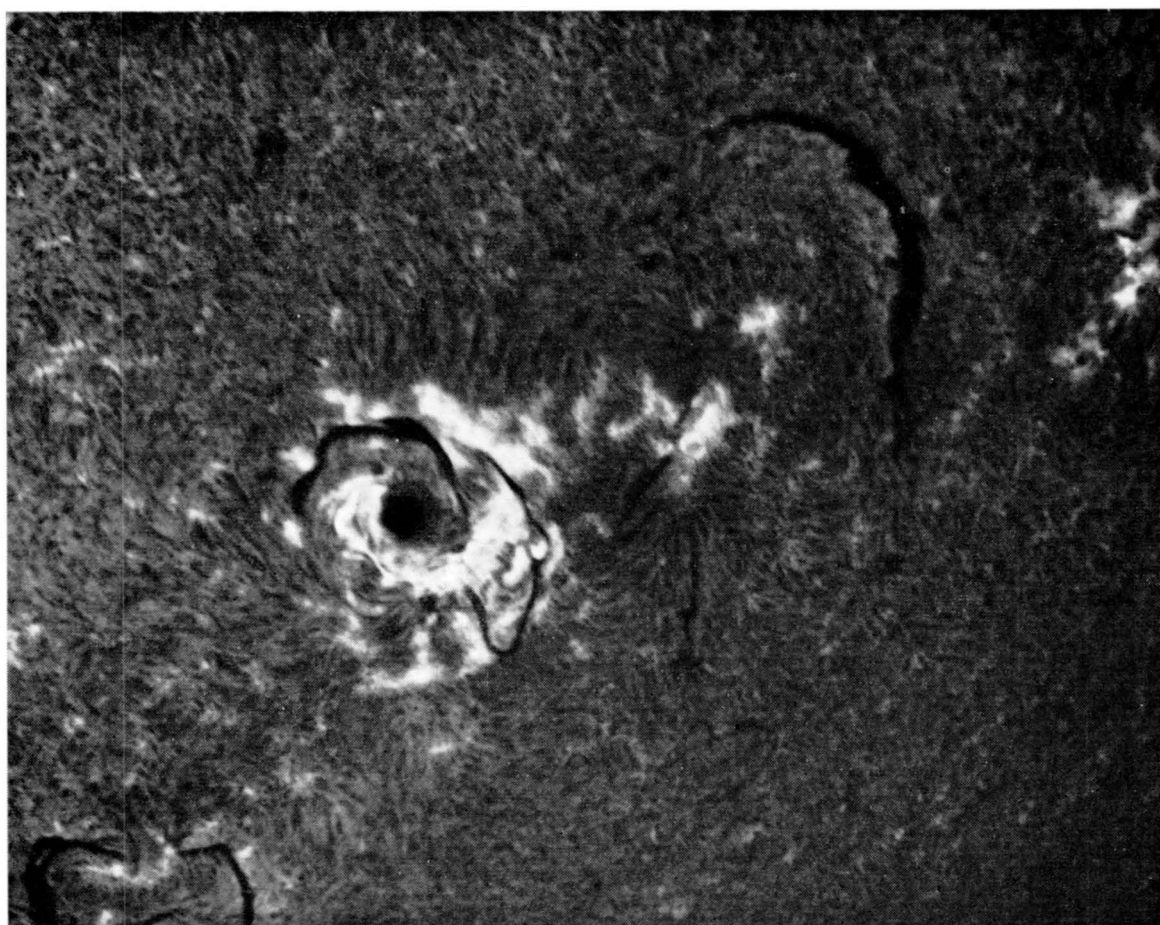


Fig. 4. Two rotations later, as Mt. Wilson 17033, one of the most active regions of this cycle (October 28, 1968. Observer, Ernest Lorenz.) It is a classic round \mathcal{P} spot completely surrounded by \mathcal{F} polarity. Most of the flares were associated with small satellite \mathcal{F} spots both following and south preceding the main spot.

4. Conclusions

The regions of occurrence of flares should give important keys to their nature; the same is true of peculiarities of active region development. The steep field gradients and polarity changes associated with flare occurrence mean that the field has a sharp vertical fold. Although some flares occur where field lines are predominantly horizontal (i.e., an extensive penumbra), these usually take the form of horizontally flowing surges, and are seldom major. (However, the major flares of March 23–26, 1967 occurred with inverted polarity well outside the penumbra; hence, with roughly horizontal structure.) The sharp change of direction of the lines of force associated with steep gradients must make possible a number of different instabilities, such as have been discussed by many authors.

The significance of inverted polarity is not clear. As Veeder and Zirin (1970) showed, there is a morphological and physical difference between following and preceding plage, resulting, no doubt, from the Hale-Nicholson Law. There is an apparent inter-

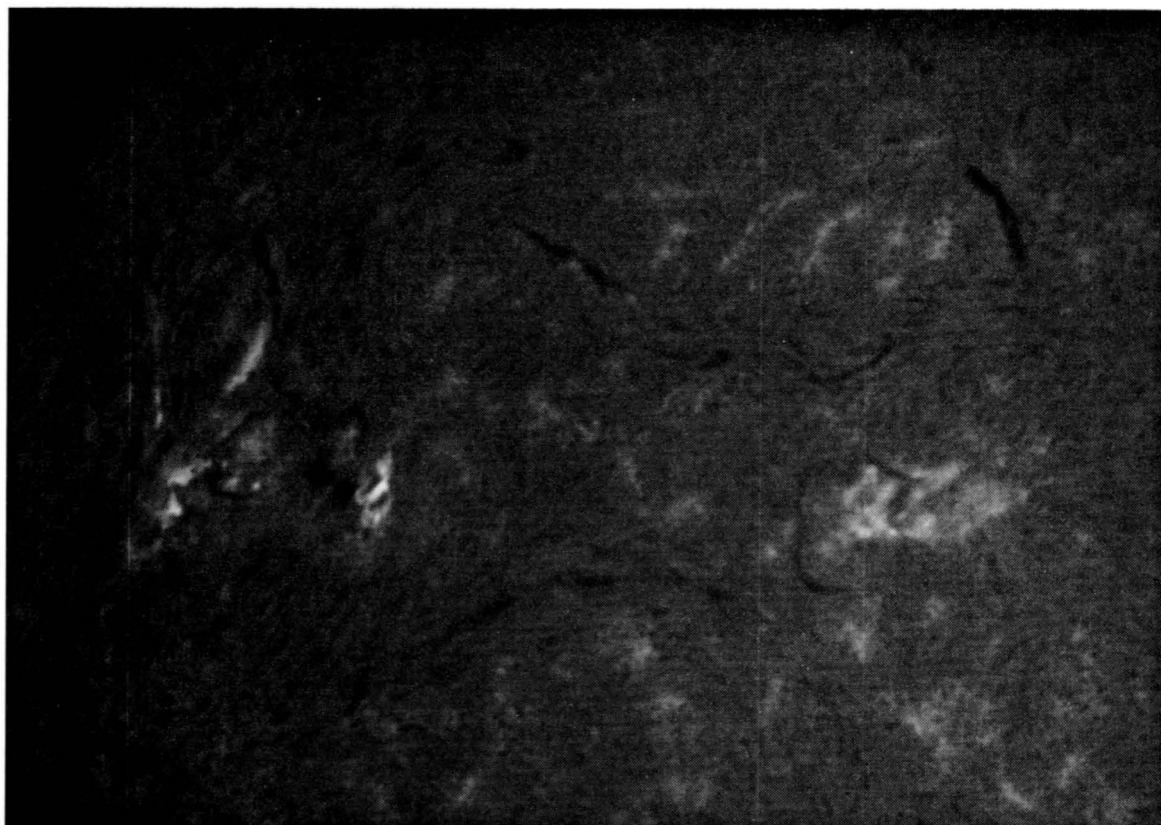


Fig. 5a. Polarity inversion as a result of bright \mathcal{F} plage growing ahead of the spot in Mt. Wilson 17097 December 23, 1968. (Observer, Ben-Zion Kozlovsky. All photos geocentric North top, West right unless otherwise noted).



Fig. 5b. Large flare in this region, December 29, 1968 1922/20 UT (observer, James Pederson).

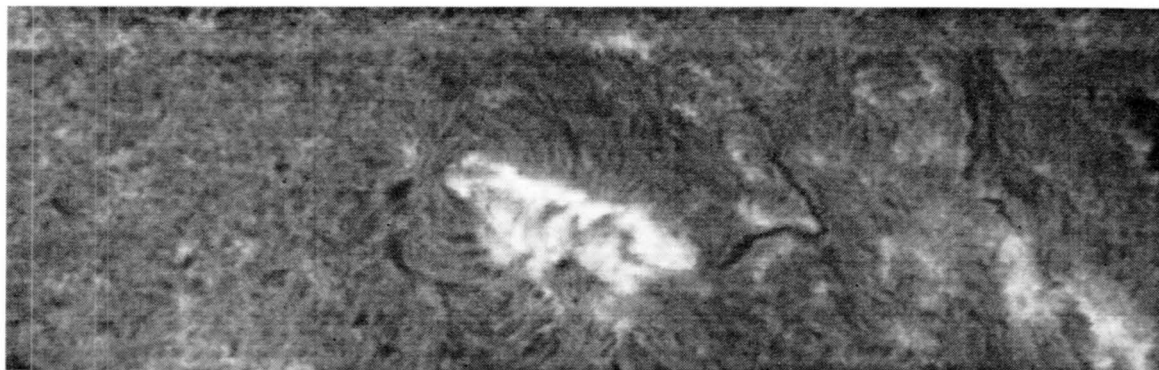


Fig. 6. Mt. Wilson 16067 July 4, 1966, spectroheliogram by P. Roberts with the 60-foot tower. This bright region with loops showed a 120° inversion, with polarities separated by an east-west line; it grew directly to huge size and great flares.

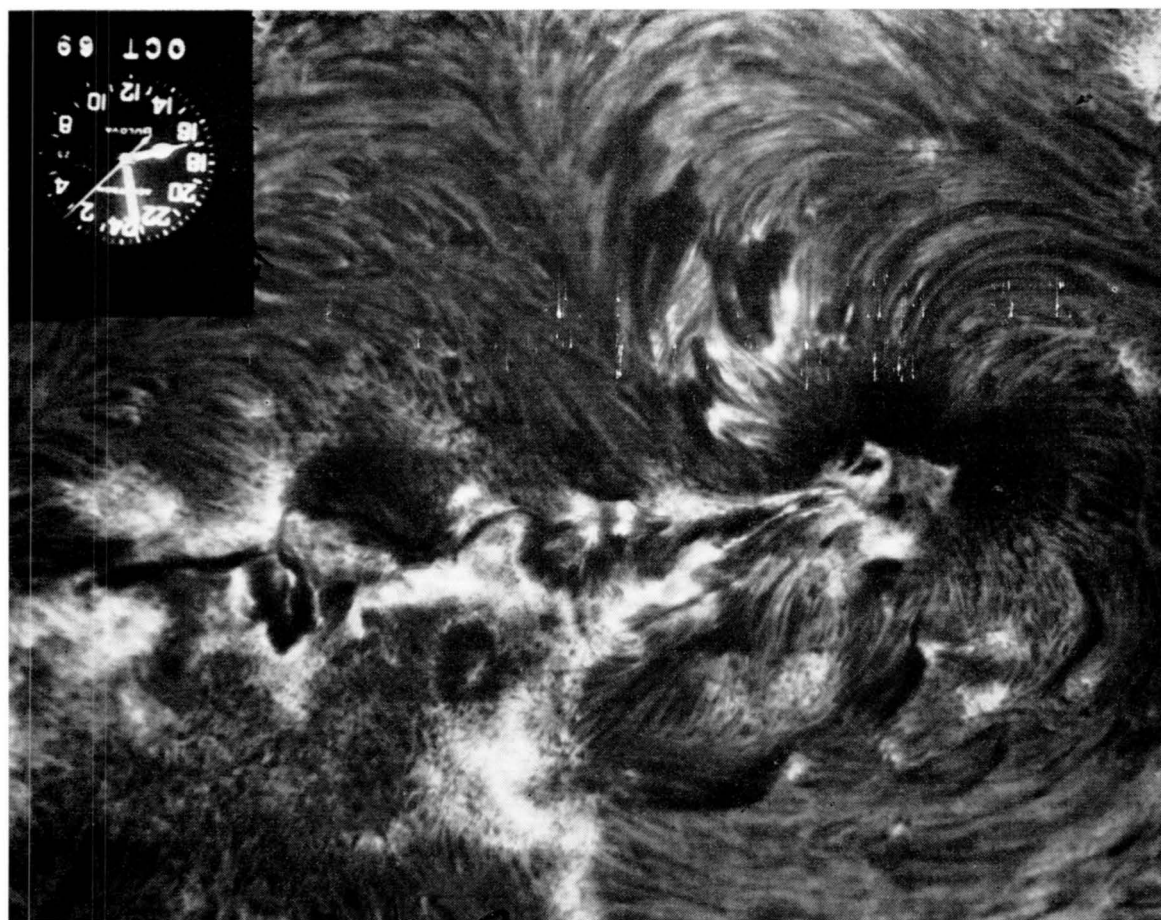


Fig. 7. Mt. Wilson 17535 photographed at the Big Bear Solar Observatory with the 10-inch refractor of Ishak I. (Observer, Lorenz.) This group is dominated by \mathcal{P} spots and was not particularly active for its size until the polarity grew disorganized after November 1. Note small satellite \mathcal{F} spots south following the main \mathcal{P} spots. Material is flowing out and in along the lines of force from these spots. A Class 1B flare accompanied their emergence of October 24. Clock is at NE.

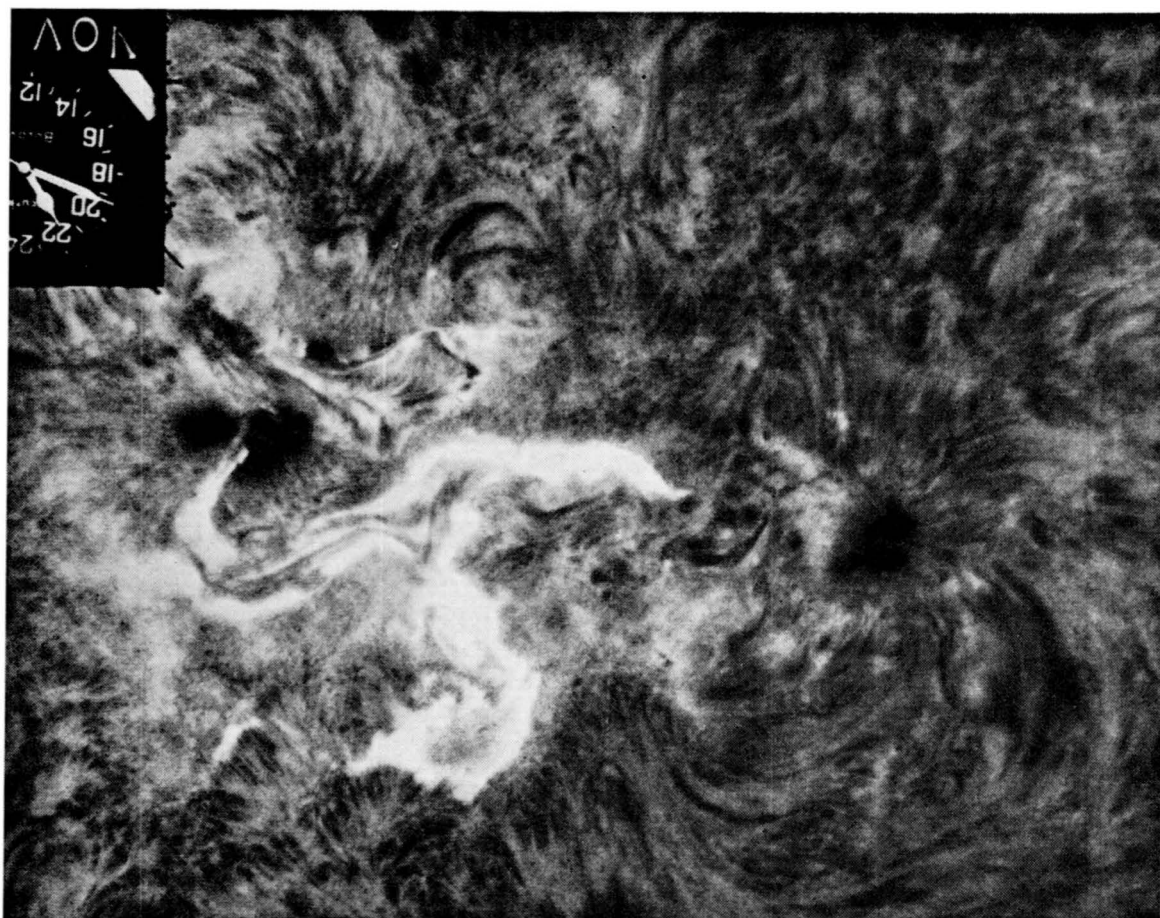


Fig 8. The same group November 18, 1969 (Ishak I, observer, Lorenz) with a Class 1 flare. The old \mathcal{P} spots are at the right, following the main region. They have lost their tail, but are far more active in this inverted situation (clock at NE).

action between the magnetic field and its surrounding which produces dominant preceding spots from symmetrically erupting fields. If the sunspots rotated with the Sun, there could arise no asymmetric forces or energy sources. If the flares occurred during the initial separation period of the bi-polar spot, we might conclude that energy was being released as the preceding spot plowed through the photosphere. But this is not the case; the flares occur when \mathcal{F} polarity erupts or exists ahead of \mathcal{P} polarity.

It is possible that these are simply the steepest field gradients that occur; i.e., that \mathcal{F} polarity simply does not approach big spots from behind. But it appears more likely that there is a strong, energetic reaction between inverted polarity and the solar rotation. The remarkable stabilization that occurs when the inverted spot rotates around to the normal position supports this view.

Emergent magnetic fields are always connected with energy release, since they are invariably connected with bright plage. However, the energy involved is easily released and not likely to cause flares (in fact, bright regions with loops characteristic of emerging fields are not particularly productive of flares). When new flux emerges in an existing region, however, it is likely to distort existing fields, and the relaxation

and accommodation process will obviously be a likely source of flares. In general, the activity connected with new fields emerging among old fields is limited to the duration of the emergence.

One would expect that the instability and energy release associated with inverted polarity would lead to rapid relaxation of that situation as well, but we have many cases where the inversion lasts for a solar rotation or more. (However, the next paper in this series shows a case of rapid relaxation.) And in cases such as McMath 10432, the inversion was apparently not the result of field emergence, but of spot proper motions. In that case, the inversion continued for another rotation and was finally resolved by dissipation of the magnetic fields. The only cases in which the reversal is removed by rotation to proper orientation are small regions with relatively simple field structure.

The principal source of flares is polarity inversion, particularly when bright plage encroaches close to a large sunspot.

The development of high activity in sunspot groups usually occurs through the emergence of new fields in stable, well-developed group. However, a few regions grow directly to a state of great activity.

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